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IONOSPHERIC EFFECTS IN SOLAR ECLIPSES

by

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1. Introduction

It is 14 years since the last international symposium on solar eclipses was held in London in 1955 (Beynon and Brown 1956). This interval of 14 years has represented the advent of the space age, and the results of this considerable period of enhanced activity on research on the earth's environment provide most of the material for this paper. My task is made easier by the fact that a summary has recently been prepared (Rishbeth 1968) of ionospheric theory pertinent to solar eclipses, based on a paper presented at the Summer School on Ionosphere held at Corfu in 1966.

Most of the information derived about the ionosphere from solar eclipses comes from a comparison of the behavior of the ionosphere during eclipse conditions with its behavior at the same solar elevation angle under full-sun conditions. In this survey, I shall discuss first those aspects of solar radiation which are important in solar eclipses, and then discuss effects in the E, F and D regions in that order; which is in fact the order of increasing complexity.

2. Solar radiation in an eclipse

As the disc of the sun is covered by the moon during a total solar eclipse, the solar flux in each wavelength region is progressively reduced, relative to its uneclipsed value. The ratio of the instantaneous solar flux at a given wavelength to its uneclipsed value is termed the "eclipse function". For visible radiation, it is unity at first and fourth contact, and zero at second and third contact for a total eclipse. For wavelengths in the ultraviolet or x-ray region, however, its behavior is quite different in two ways. First, regions of increased brightness on the solar disc may cause the eclipse function to change irregularly with solar obscuration; and second, radiation from outside the visible disc may give an eclipse function which does not become zero even when the whole visible disc is covered (in other words, an eclipse which is total for visible light may be annular for other wavelengths).

As an example of a direct measurements of this first effect, Figure 1 (Landini et al., 1966) shows the variation of solar x-ray intensity in three wavelength regions during the solar eclipse of May 20, 1966, as seen by the

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SOLRAD 8 satellite. For ultraviolet radiation in the 1225-1350 Å region, the eclipse function decreased fairly uniformly with time. At the x-ray wavelengths (1-8 and 8-16 Å) which produce ionization in the D and lower E regions of the ionosphere, however, the solar disc was very non-uniform in brightness. Any analysis of D- and E-region ionization must use an eclipse function for the appropriate wavelength region, rather than simply the unobscured fraction of the visible disc. Unfortunately, it is quite unlikely that one of the few solar radiation satellites will be available in the path of any given eclipse, particularly during its maximum phase. Photographs of the solar disc using rocket spectrographs at various wavelengths are highly desirable, in that they show the contribution of active regions inside and outside the disc with greater resolution than can be obtained using available techniques from pictures of the full sun.

Our lack of knowledge as to the precise amount of coronal radiation which comes from outside the solar disc is particularly important for the interpretation of E-region ionospheric measurements during solar eclipses. For this region, x-ray and ultraviolet radiation are approximately equally important in producing ionization. Few observations are available of the residual x-ray intensity during totality. The Naval Research Laboratory group (Friedman 1962), using rocket-borne photometers during the solar eclipse of October 12, 1958, found a residual intensity at totality in the 44-60 Å x-ray band of about 10-13 percent of the full-sun emission. Smith *et al.* (1965) found 22 percent residual intensity during the partial eclipse of July 20, 1963 at Ft. Churchill, Canada, when the visible disc was 9.5 percent uncovered. Their best interpretation of the E-region ionization data was that half of the radiation followed the x-ray eclipse function, and half followed the unobscured area of the visible disc.

Lacking such detailed information as that illustrated in Figure 1, for most eclipses, it is difficult to make assumptions which are any more sophisticated than those just outlined. There is an obvious need for more accurate determinations of the x-ray intensity as a function of altitude in the solar atmosphere; these could be made, for example, by a rocket-borne spectrograph of relatively low angular resolution, fired during the early period of visible-light eclipse totality.

3. The E region during a solar eclipse

The typical behavior of E-region ionization during a solar eclipse is well illustrated by Figure 2, from Szendrei and McElhinny (1956). The minimum of electron density occurs close to the time of second and third contact, and is about half that on the normal day. Also illustrated on Figure 2 are several curves found by solving the continuity equation for the ionization, on the assumptions that the rate of electron production was proportional to the unclipped area of the visible disc; and that the recombination coefficient of the ionization was constant with values from 5×10^{-9} to $2 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$. Evidently, a high recombination coefficient produces a much sharper minimum in the electron density than that observed; while a low value produces a minimum which is much delayed from the time when the minimum electron density was observed. Many attempts were made to explain this discrepancy on the basis on an effective recombination coefficient which varied during the eclipse; for instance, Bates and McDowell (1957) suggested that two ions with quite different recombination coefficients might be present, resulting in an effective recombination coefficient that changed throughout the eclipse as the relative concentrations

of the two ions changed. Bowhill (1961) showed that one could obtain a reasonably good fit to various E-region experimental results by assuming ions with recombination coefficients of about 6×10^{-9} and $6 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$. The ions were tentatively identified as those of nitric oxide and molecular oxygen. However, it is now known from laboratory measurements that the correct recombination coefficients for these ions are about 5×10^{-7} and $2 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$, respectively, so obviously this explanation is not tenable.

Some attempts have been made to reconcile the experimental results with a single value of recombination coefficient by assuming that strong discrete sources of radiation are present within the visible solar disc. However, such analyses have nearly always concluded that very strong limb brightening is present, but with the western limb much brighter than the eastern. There seems to be no physical reason why this would be expected; and, in fact, it can be shown that this apparent result follows naturally from the assumption of a recombination coefficient large enough to prevent E-region ionization from disappearing more rapidly than is observed during the period of totality. Evidently, it is the neglect of residual radiation at totality which causes the difficulty.

Taubenheim and Serafimov (1969) have established an interesting model for the May 1966 solar eclipse in southern Europe, in which they assumed a coronal contribution to the total ionizing intensity, proportional to the intensity of the green coronal line. The recombination coefficient they estimate (greater than $8 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$) is in much better agreement with laboratory measurements than results typically obtained for solar eclipses.

Another argument in favor of the high values for recombination coefficient is the symmetry of the E-region electron density variation about the center of totality. A recombination coefficient of $5 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$, with a minimum electron density of $5 \times 10^{-4} \text{ cm}^{-3}$, would yield a time delay of the minimum electron density relative to the center of totality of about 20 sec, scarcely detectable with normal experimental techniques. Lower recombination coefficients (say, $10^{-8} \text{ cm}^3 \text{ sec}^{-1}$) would give about 17 min time delay, significantly greater than commonly observed (see, for instance, Figure 3).

If, then, we accept the position that the E-region ionization is essentially in photoequilibrium throughout even a total solar eclipse, it follows that the minimum value of the electron density should be due primarily to x-radiation from the sun. Since this radiation is substantially greater at solar maximum than solar minimum, it should be found that in a period of low sunspot activity the E-layer electron density decreases on the average by a larger ratio than in a time of high sunspot activity. It would be interesting to review past eclipses to see if this hypothesis is supported by E-layer critical frequency measurements.

It has been known for many years that the daily variation of the earth's magnetic field is affected by the passage of an eclipse (Bauer 1910). The effect is apparently due to a change in the conductivity of the E-region, produced by the decreased ionization in the eclipse path. Bomke *et al.* (1967) have used this effect to estimate the E-layer recombination coefficient during the November 1966 solar eclipse in Peru, by subtracting the diurnal variation of the magnetic field on a normal day from the eclipse day results. The difference field, shown in Figure 4, exhibited a time delay of nearly three minutes relative to the optimum location of the E-layer shadow, which he suggested might be due

to a finite recombination coefficient for the E-region ionization. However, Matsushita (1966) has pointed out that magnetic variations in solar eclipses must be interpreted with caution, as the effect of the eclipse is to insert a partial insulator in the path of the dynamo current system, and that the dynamo current may be diverted around the obstacle; resulting in effects that are hard to estimate quantitatively.

Finally, there have recently been some measurements of ion composition in the E region during a solar eclipse. Figures 5 and 6 (Narcisi et al. 1969) show the relative abundances of various ions on a control day and during totality, respectively, for the November 1966 total solar eclipse in southern Brazil. While the totality measurements extended to only a little above 95 km, the pattern of behavior is clearly that there is no substantial change in E-layer ion composition during the eclipse. This lends further support to the idea that photoequilibrium is maintained even at totality; resulting in a nearly constant ratio of ion abundance, even though the recombination coefficients may not be identical. Such change as is evident is in the direction of an increase in the relative abundance of nitric oxide ions. Since, under full-sun conditions, there is an approximately equal contribution from x-rays and from the ultraviolet Lyman- β radiation, the fact that the eclipsed sun radiates primarily x-rays, which ionize all atmospheric constituents (including atomic oxygen and molecular nitrogen, which presumably contribute to the nitric oxide ion concentration), would lead one to expect the relative abundance of molecular oxygen ionization to decrease somewhat.

4. The F region during a solar eclipse

The key problem in the interpretation of F-region ionospheric results during solar eclipses is that of distinguishing chemical from dynamic effects (Rishbeth 1968). If ionization movements can be neglected, the systematic variation of ionization production rates through a solar eclipse can give good measurements of the rate of recombination of F-region ionization, since the time constants involved (unlike those in the E region) are comparable with the eclipse duration.

Due to the effects of the earth's magnetic field, it happens that dynamic effects are much less important in the F region at low latitudes, where the magnetic field is nearly horizontal. The 1958 experiment of Van Zandt et al. (1960), reproduced here on Figure 3, illustrates the type of behavior that is typically encountered. The minimum electron density is delayed after totality by an amount which increases with altitude; and the depth of the minimum in electron density decreases correspondingly. Values of the electron loss coefficient deduced from these eclipse results are in good accord with recent laboratory measurements of ion-atom interchange rate coefficients, when combined with models of F-region molecular oxygen and nitrogen concentrations. Generally similar results were found by Skinner (1967) for the October 1959 eclipse in Nigeria.

A complication in F-region chemistry in solar eclipses is the observation that if the F₁-layer is absent prior to the eclipse, it usually appears after the eclipse begins. As is well known, the altitude of the F₁-layer maximum is close to the transition in the ion composition between the predominantly molecular ions of the E region and the predominantly atomic ions of the F region. De Jager and Gledhill (1963) have successfully explained this curious

F1-layer behavior in terms of the change in character of the loss process at the altitude of the ion composition transition.

At medium latitudes, the behavior of the earth during an eclipse is quite different. Figure 7 shows a profile of the F2-layer electron density measured with the Thomson-scatter radar at Millstone Hill by Evans (1965). Relative to the control days, the electron density on the eclipse day actually increases. Careful comparison of Figures 7(a) and 7(b) shows that the electron density has increased below 450 km altitude during the eclipse, but has decreased above that altitude. Evidently, therefore, the decrease in ionization production in this eclipse is relatively unimportant compared with transport effects; the ionization in the topside of the F layer has migrated down the field lines, resulting in an enhancement of the electron density at the F2 peak.

The reason for this rapid diffusion of topside ionization is shown on Figure 8, depicting the ratio of electron to ion temperature (also measured by the Thomson-scatter technique) on the control days and on the eclipse day. Whereas on a normal day the ratio is about 2, on the eclipse day it falls to as low as 1.2 (and it can be shown that the change involved is mostly in the electron rather than in the ion temperature). The distribution of ionization in the topside of the F layer is controlled by the plasma scale height, which in turn is determined by the sum of the electron and ion temperatures. Since this sum has decreased by approximately 30 percent during the eclipse, it follows that the plasma scale height must have decreased by a like factor, resulting in a sudden downward diffusion of ionization from the topside into the F2-layer peak; increasing it by the amount shown. On this basis, therefore, one would expect that a measurement of total electron content of the ionosphere would not show this increase; and, in fact, might be expected to decrease, if anything. Measurements in the same eclipse by Klobuchar and Whitney (1965) in fact showed a decrease in total electron content at the time of the eclipse.

This strong variation in the thermal structure of the ionosphere during an eclipse is due to the very rapid nature of the processes by which the ionization is heated (Geisler and Bowhill, 1965). Photoelectrons produced throughout the F region migrate along the lines of the earth's magnetic field, giving up energy by inelastic collisions to the neutral atmosphere, and by Coulomb interactions to the ambient ionization. If produced above 400 km, they may in fact escape from the ionosphere and continue along the field lines to the geomagnetic conjugate point. If the source of these photoelectrons is removed by a total eclipse, it takes only a few seconds for the ionosphere to cool to a temperature approaching the neutral gas temperature, the only remaining heat source being conduction from the hot protonospheric ionization in the same field tube. The ionization itself, of course, will react much more slowly to changes in thermal structure, the rate being limited by the diffusion of ionization to the neutral gas. However, it will be much more rapid at the highest altitudes. A proper solution of the eclipse problem requires establishing the time-varying continuity equation for the ionization, including transport effects due to changes in the thermal structure. Work on this subject is only beginning (Cho and Yeh, 1970), and has not yet been applied to the solar-eclipse case.

An interesting aspect of F-region eclipse effects is the possibility of observing perturbations in the ionosphere at the point conjugate to that eclipsed (Haubert and Laloe, 1963; Bousquet *et al.*, 1967). One might think of an association between the contraction of the eclipse F2 layer, with the resultant drop in plasma pressure at the top of the ionosphere, and a movement of ionization

from the conjugate hemisphere along the field lines, which would tend to reduce the peak electron density at the conjugate point. The time taken for a compressional wave to travel from one hemisphere to the other through the protonospheric plasma would imply a delay of several hours in the conjugate effect. An alternative possibility arises from the eclipsing of the source of conjugate photoelectrons. This would lead to a decrease in the heat input at the conjugate ionospheric point, coincident with the center of the eclipse; therefore, presumably, a decrease in the electron temperature, and an increase in the F2-layer maximum electron density. Present results do not seem to be conclusive in this regard; perhaps a direct measurement of electron temperature at the conjugate point would prove helpful.

5. The D region during a solar eclipse

The study of the D region during eclipse conditions, in common with the study of the normal D region, has suffered from the difficulty of measuring the very small electron densities (less than 10^4 cm^{-3}) which occur below 90 km. However, measurements of amplitude and phase of a VLF radio signal during an eclipse (Crary and Schneible 1965) in July 1963 showed a change in the phase height of reflection, with maximum excursion delayed a few minutes from the time of maximum obscuration at the center of the VLF path.

Smith et al. (1965) made direct rocket measurements of electron current collected by a Langmuir probe in the D region during a partial solar eclipse in July 1963 at Fort Churchill, Canada. The electron current curves from the four rockets are shown on Figure 9. Rocket 1 was fired just before maximum phase of the eclipse, when the visible disc was about 9 percent uncovered; rocket 2 ten minutes later, when the visible disc was about 14 percent uncovered; rocket 3, with the disc 59 percent uncovered; and rocket 4, with the disc 97 percent uncovered. Even though the proportionality constant between probe current and electron density may change with altitude below 90 km, it is obvious that the electron density at 70 km dropped dramatically during the maximum phase of the eclipse; by a greater factor, in fact, than even the area of the visible disc. We shall see later that this result is a key factor in interpreting the ion chemistry of this region.

During the November 1966 eclipse in southern Brazil, Mechtly et al. (1969) were able to measure electron densities with good absolute accuracy by a combination of the Langmuir-probe and radio-propagation techniques on a series of four Nike-Apache rockets. The trajectories for the four rockets are explained on Figure 10, and the electron density results are shown on Figure 11. Between rockets 2 and 3, which were in the beginning and end of totality, respectively, at 80 km altitude, the electron density dropped by a factor of three between about 78 and 85 km, and by a much larger factor below 75 km. On the other hand, the E-region ionization at altitudes about 90 km decreased by almost the same factor at all altitudes, and did not change appreciably during totality.

Positive ion densities were measured by Bowling et al. (1967) using a negatively biased probe on a series of sounding rockets during the solar eclipse of May, 1966, in Greece. They found positive ion densities which decreased from about 3000 cm^{-3} to about 300 cm^{-3} at 70 km altitude, between full sun and totality.

Measurements of positive ion composition by Narcisi *et al.* (1969) are shown on Figures 5 and 6. In contrast to the results of Bowling *et al.*, no very large decrease was found in the ion concentration at 80 km altitude; though there was a greater relative abundance of doubly hydrated protons during the measurements at totality.

In interpreting these results, Sechrist (1970) has suggested that electron-ion recombination is the major loss process for electrons above 80 km altitude, and has deduced a recombination coefficient of about $4 \times 10^{-5} \text{ cm}^3 \text{ sec}^{-1}$ between 78 and 86 km from the results of Mechtly *et al.* (1969). This very large recombination coefficient is suggested to be associated with the recombination of hydrated protons with electrons, measurements of which are not yet available in the laboratory. It is interesting to note that both Bischoff and Taubenheim (1967) and Crary and Schneible (1965) have deduced similarly large recombination coefficients from VLF data.

Below 75 km, the extremely rapid disappearance of ionization can be explained only by attachment, probably initially to molecular oxygen by a three-body process, followed by charge exchange with ozone. Since atomic oxygen has the ability, through associative detachment, to compete with the ozone for the available molecular oxygen negative ions, the rate at which negative ions of ozone are formed probably depends critically on the atomic oxygen-to-ozone ratio. Keneshea *et al.* (1969) have shown that this ratio can change dramatically during an eclipse; for example, Figure 12 shows their calculation of various minor constituents at 70 km altitude for the circumstances of the partial eclipse at Fort Churchill, Canada in July 1963. The ratio of these constituents changes by more than an order of magnitude during this eclipse; and the effective loss coefficient for electrons would therefore be expected to increase by a corresponding ratio. It is possible that the anomalous behavior of the electron density below 75 km near totality could be explained on this basis; namely, a variation in loss coefficient throughout the eclipse produced by the disappearance of the dissociating influence of ultraviolet solar radiation from the visible disc.

6. Conclusion

Interpretation of ionospheric measurements taken during solar eclipses, in summary, will need to take into account the following considerations:

1. The non-uniformity of solar radiation, both inside and outside the solar disc;
2. The varying ion composition of the D and E region;
3. Changes in electron and ion temperature in the F region, and the transport effects associated with them;
4. Changes in minor constituent concentrations in the D region, and their effects on electron loss coefficients and ion chemistry.

In addition, it would be greatly advantageous to coordinate measurements using ground-based techniques such as sweep-frequency reflection sounding, satellite Faraday rotation, and Thomson-scatter sounding, with space techniques involving radio and direct sensing experiments on rocket vehicles.

It is certain that eclipse experiments will remain a highly useful tool for exploring transient properties of ionospheric constituents, and determining rates for chemical and transport processes associated with them.

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CAPTIONS TO FIGURES

- Figure 1. Solar radiation in three bands measured by the SOLRAD 8 satellite (Landini et al., 1966).
- Figure 2. Theoretical and experimental peak electron densities for the E layer (Szendrei and McElhinny, 1956).
- Figure 3. E- and F-region electron densities at fixed heights during an equatorial eclipse (Van Zandt et al., 1960).
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- Figure 9. Electron density profiles in the D and lower E regions assuming probe current proportional to electron density (Smith et al., 1965).
- Figure 10. Percentages of visible solar disk, and elapsed times since commencement of totality at each position for four rockets launched in the November 1966 eclipse in Brazil (Mechtly et al., 1969).
- Figure 11. Electron densities measured with four rockets during the November 1966 eclipse in Brazil (Mechtly et al., 1969).
- Figure 12. Minor constituent concentrations calculated for 70 km altitude, for the 1963 eclipse at Fort Churchill, Canada (Keneshea et al., 1969)

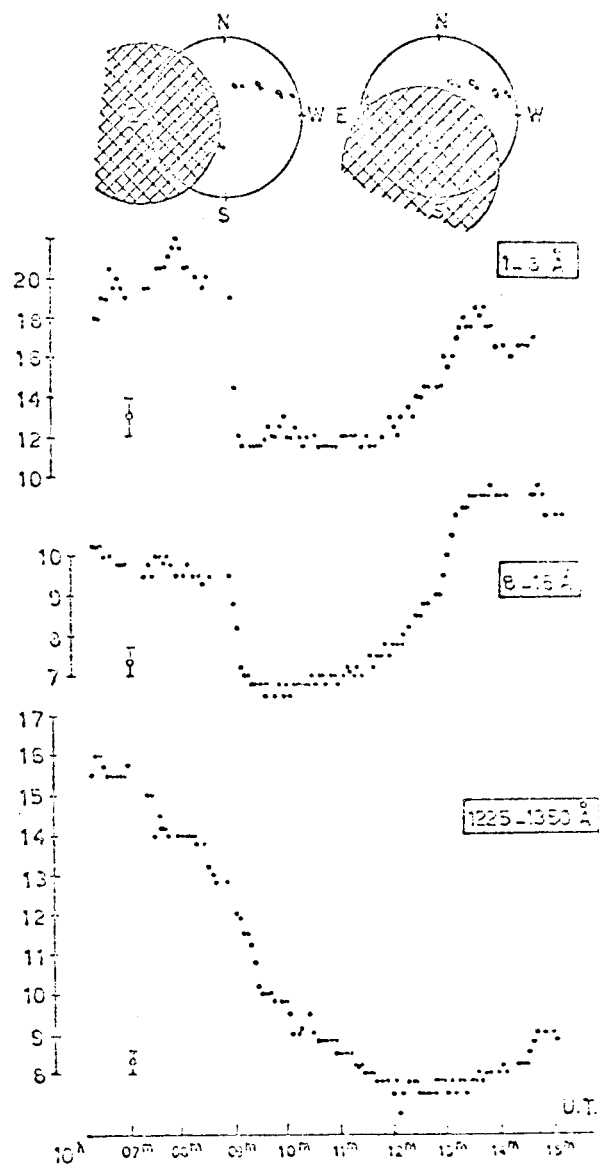


Figure 1

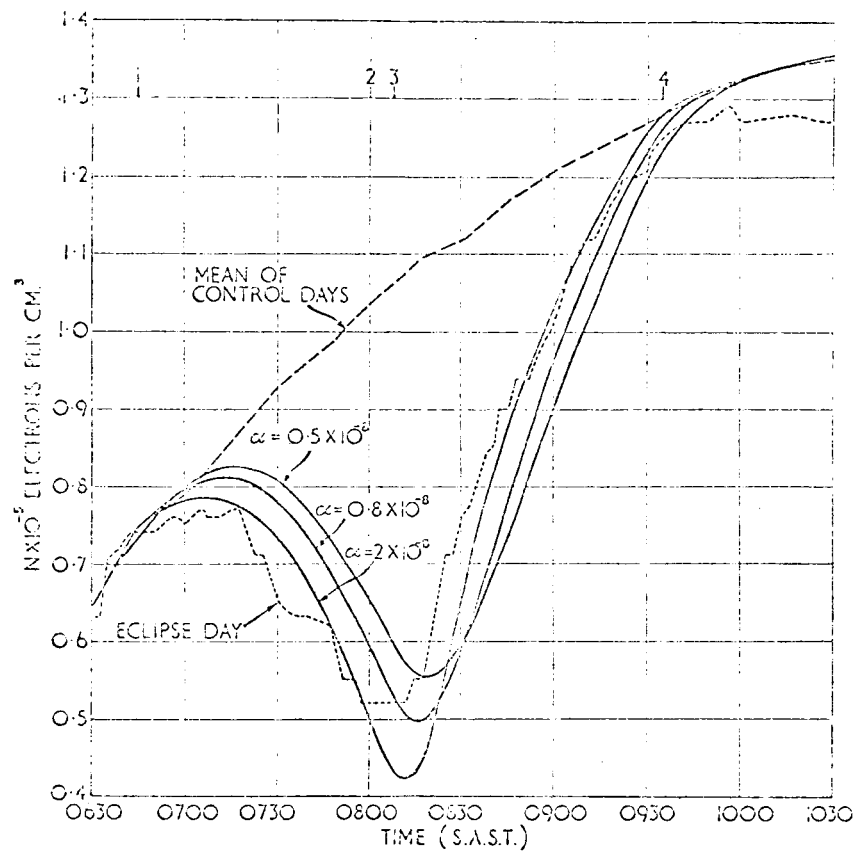


Figure 2

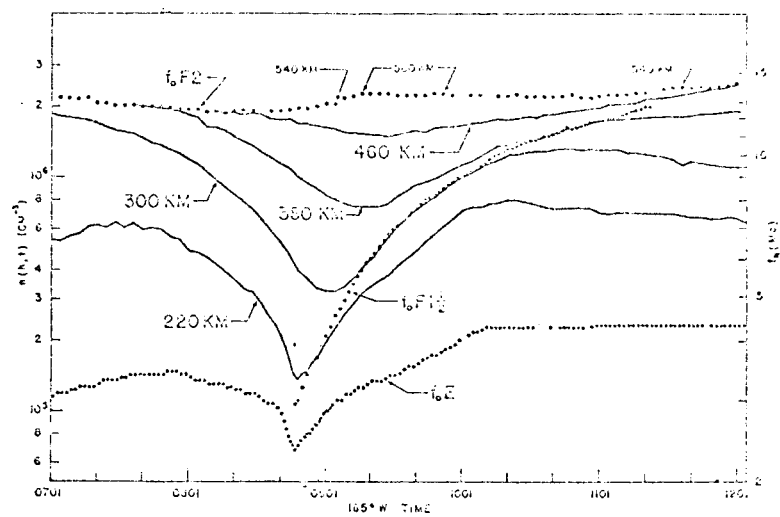


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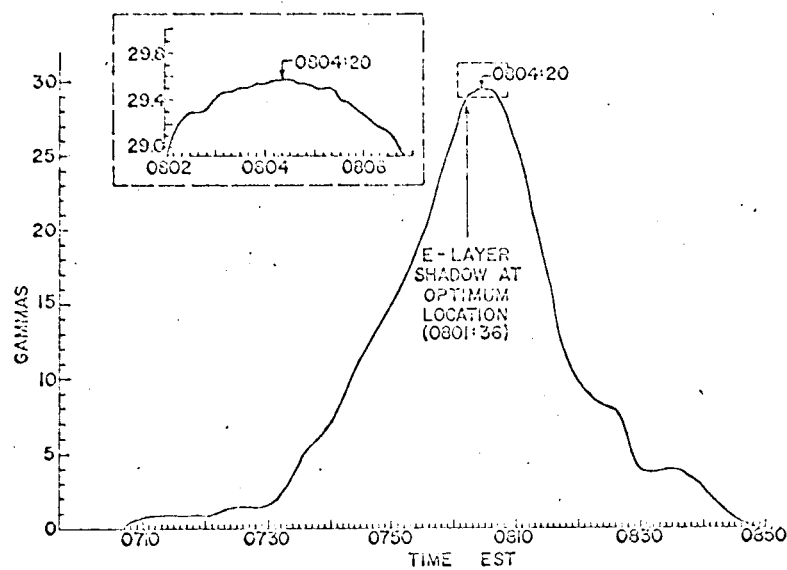
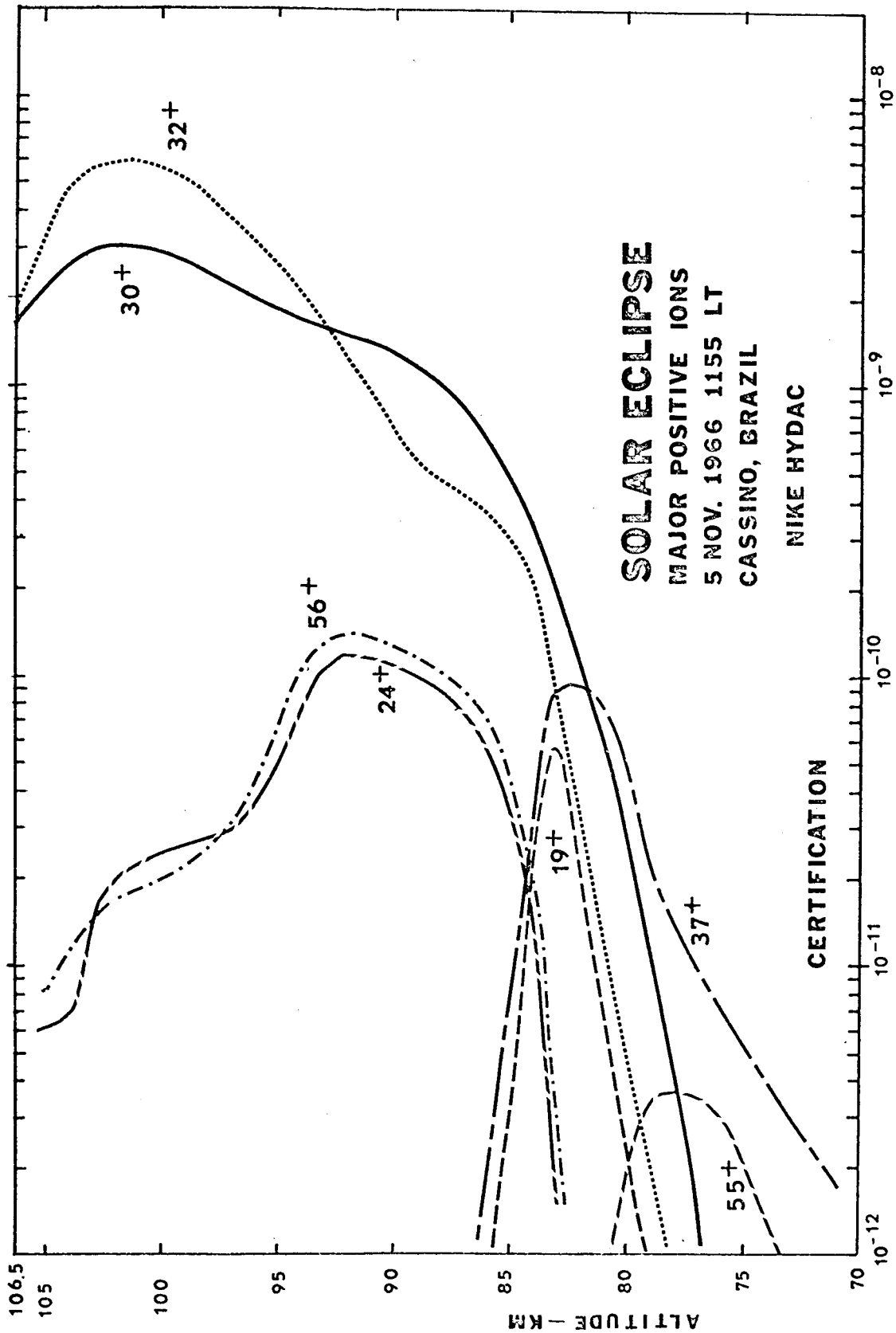
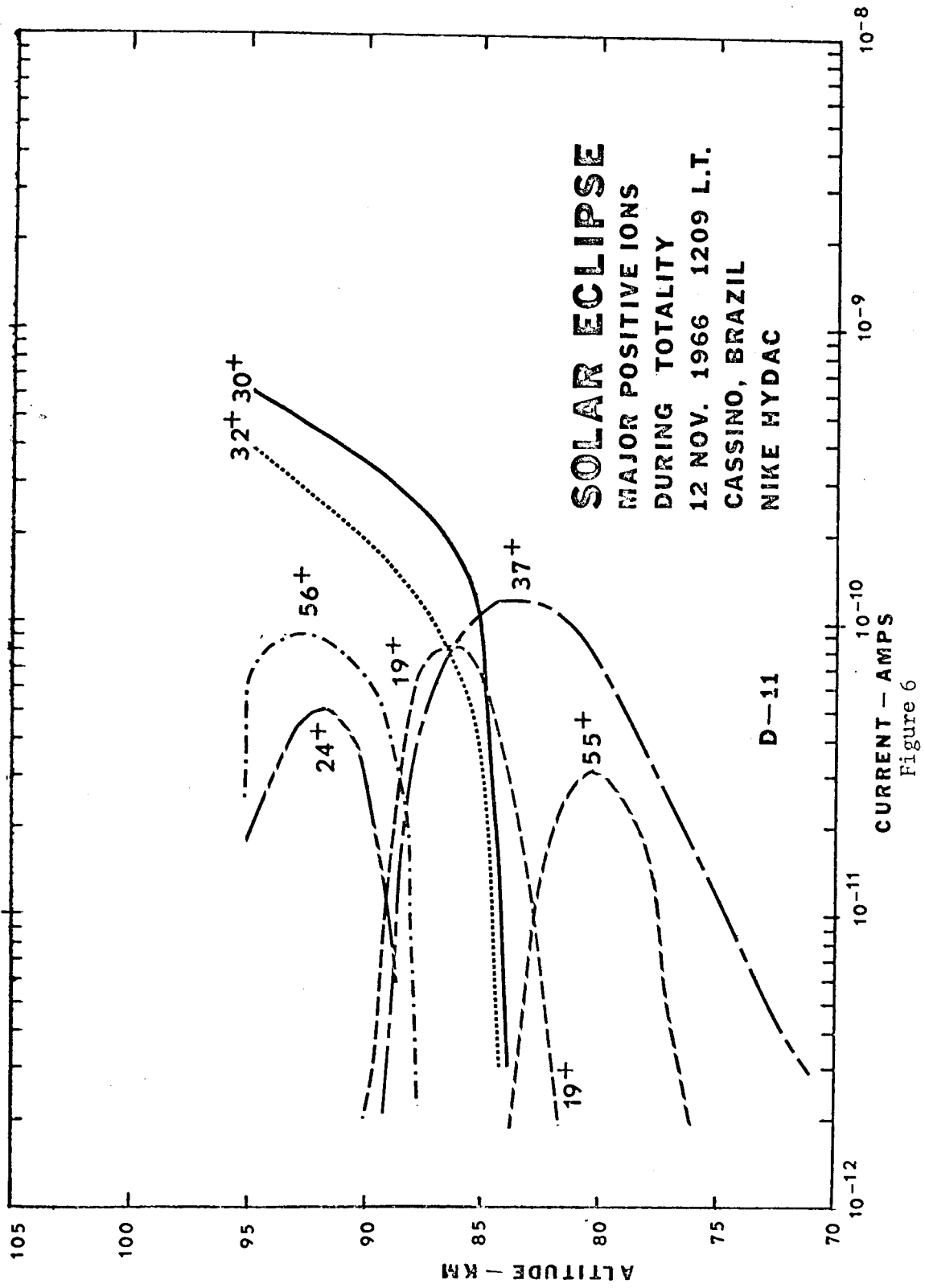
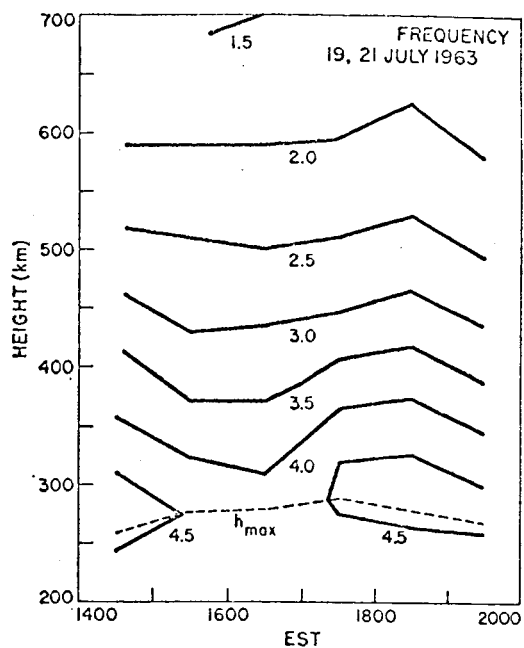


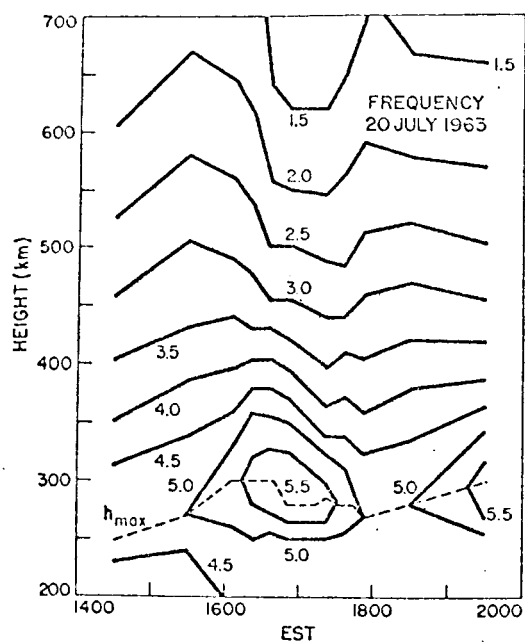
Figure 4





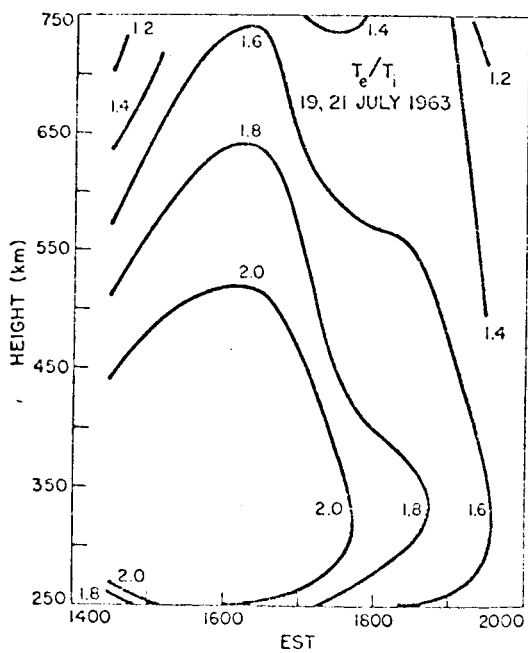


(a)

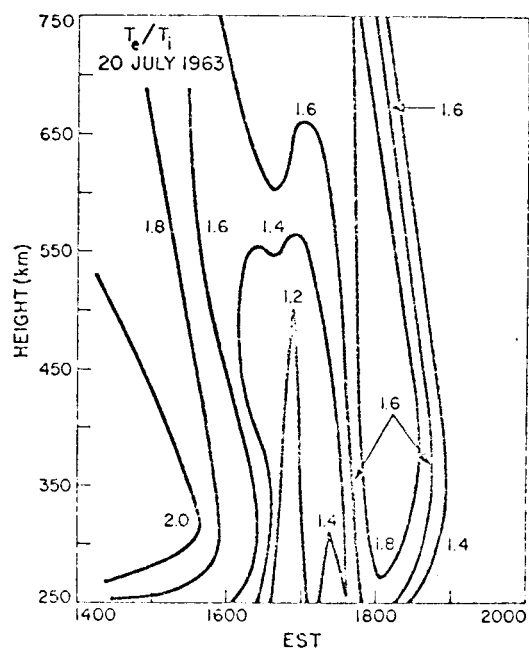


(b)

Figure 7



(a)



(b)

Figure 8

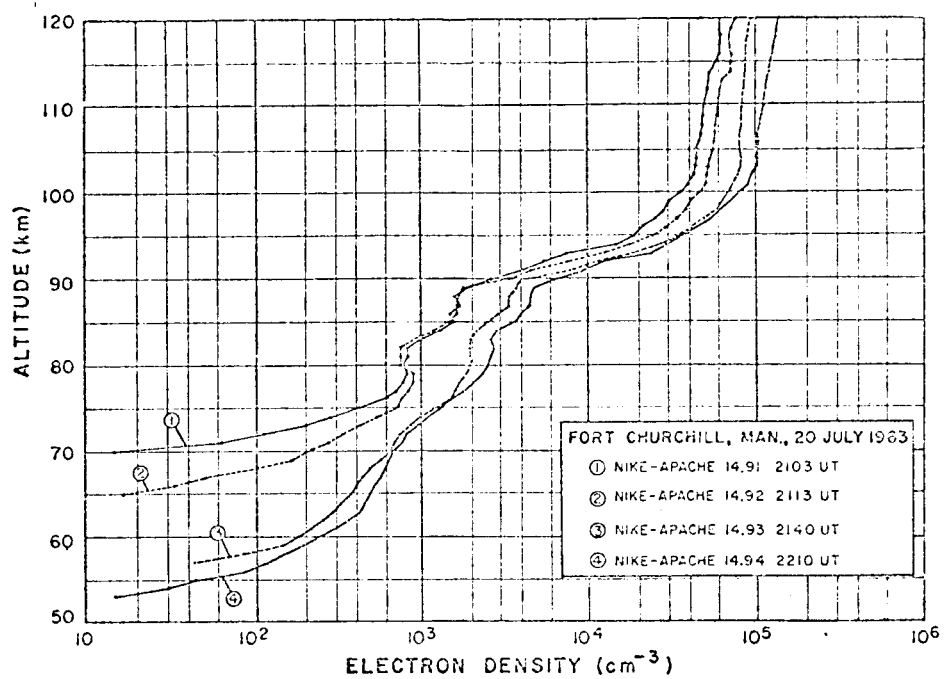


Figure 9

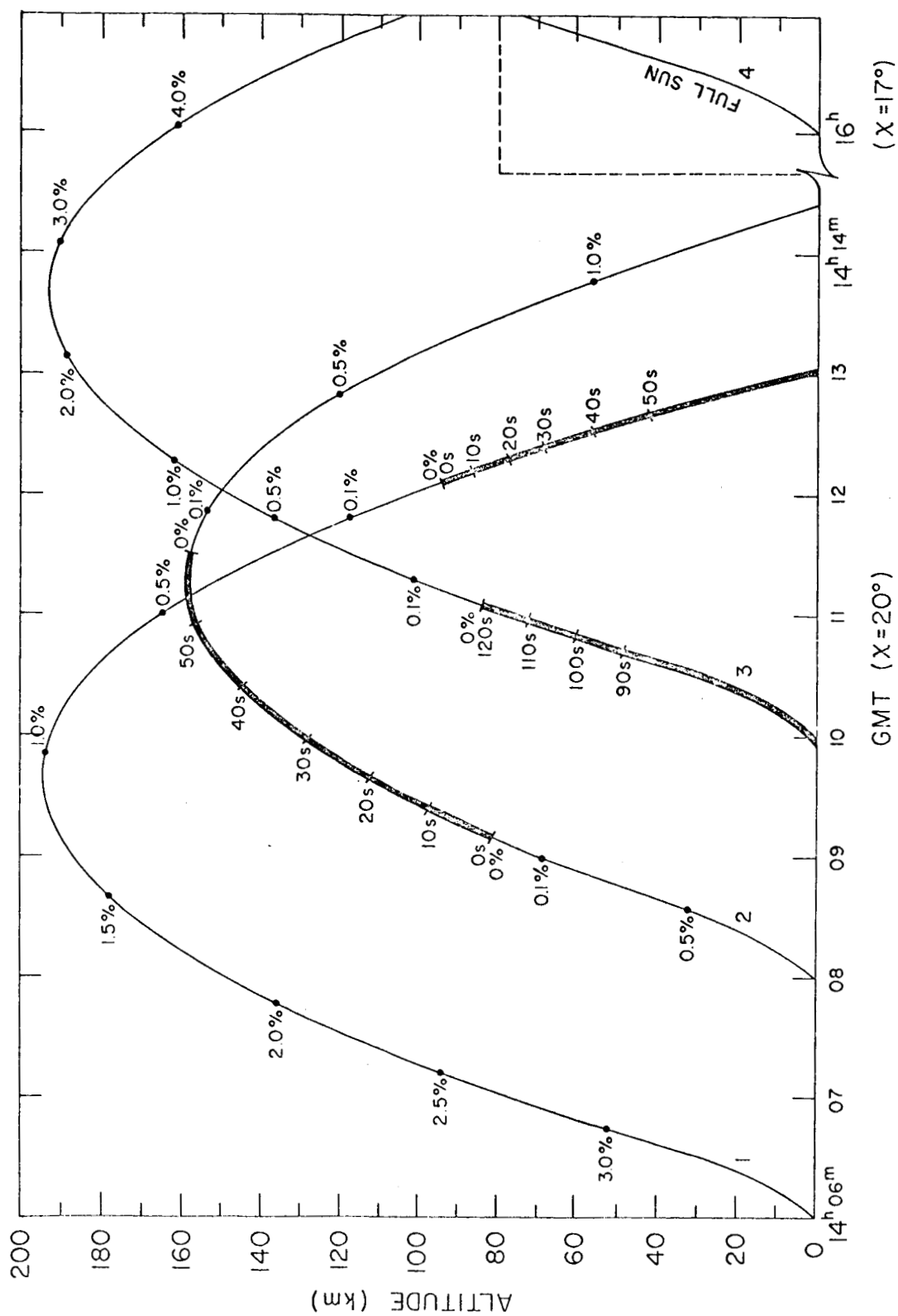


Figure 10

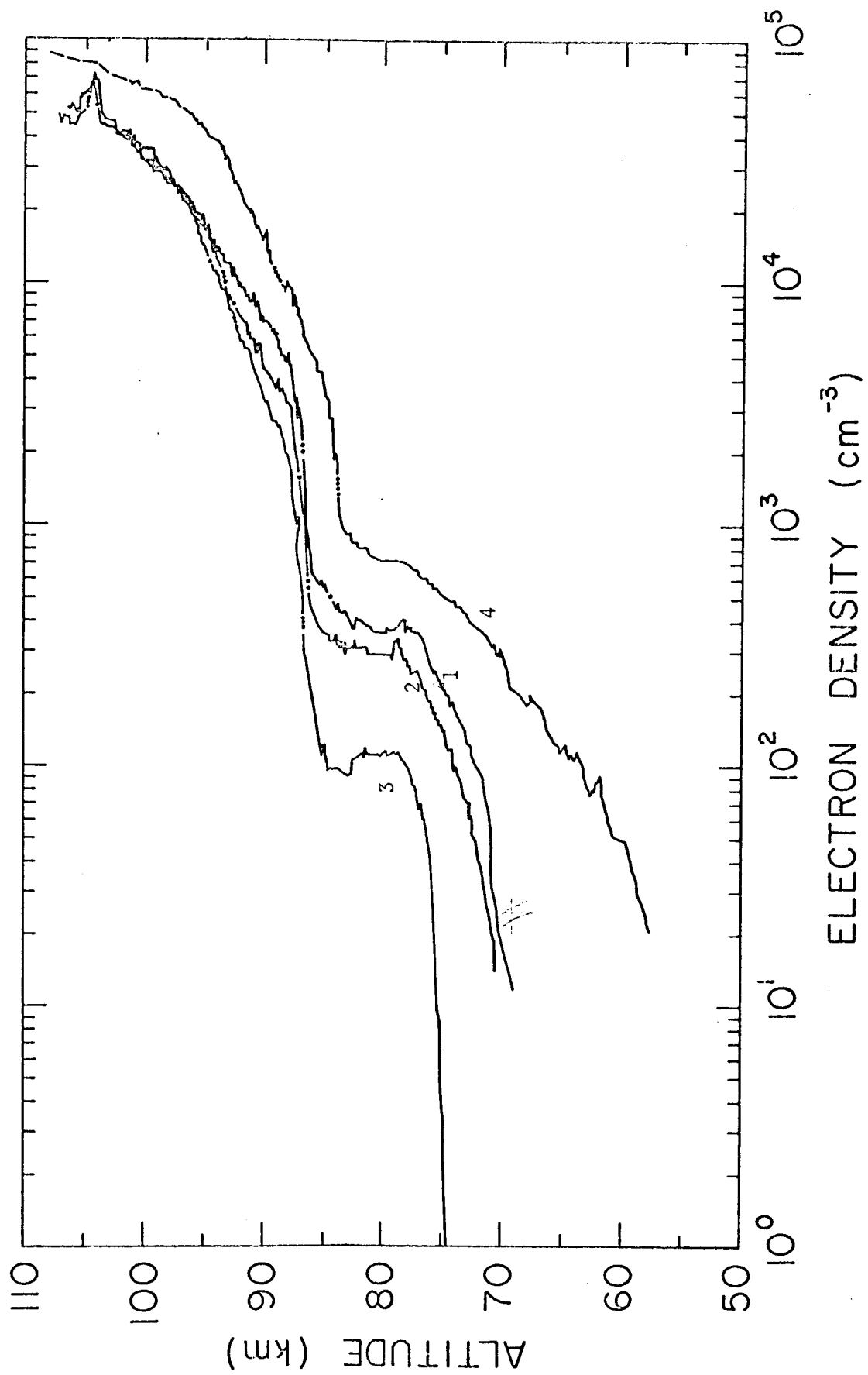
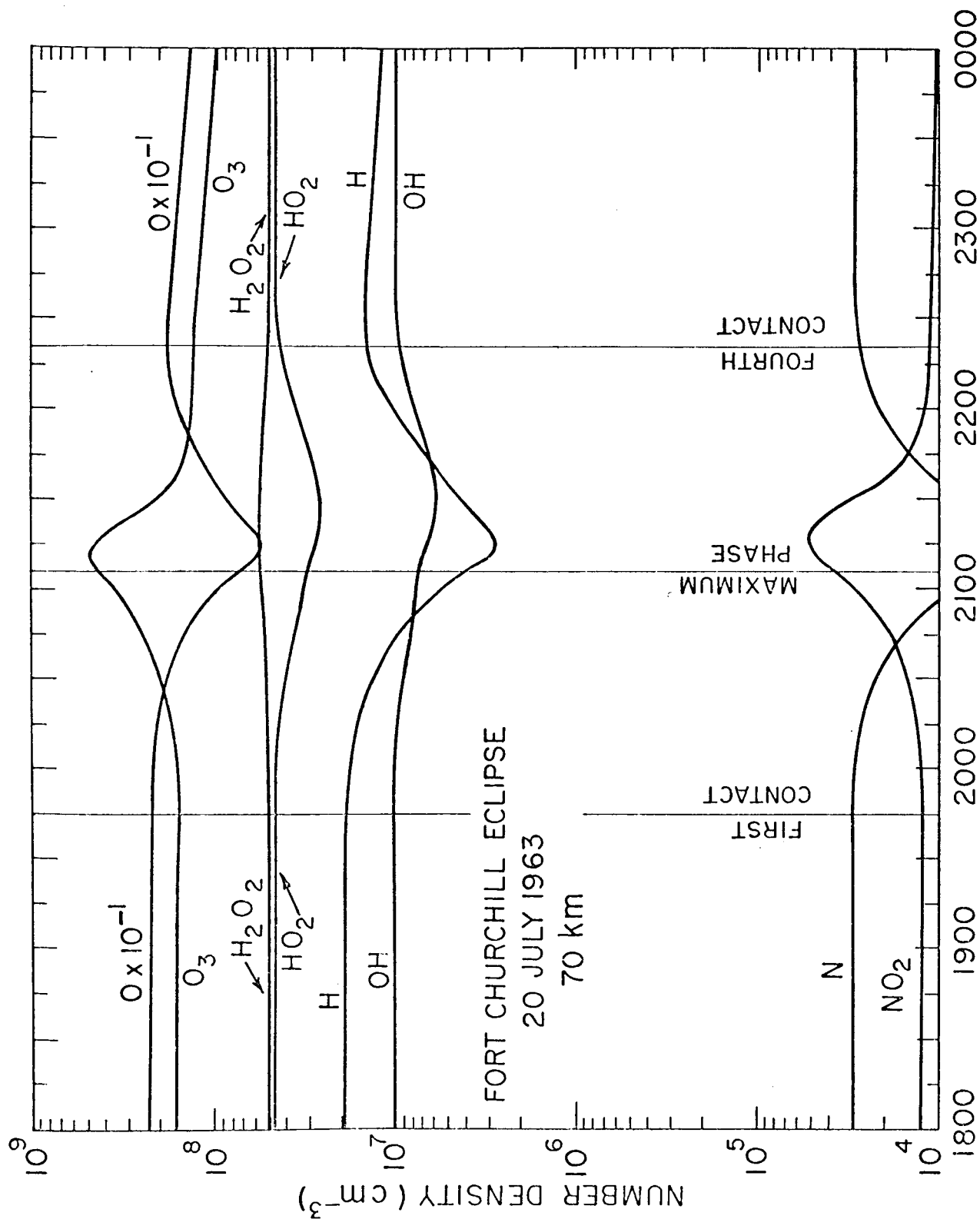


Figure 11



UNIVERSAL TIME (HOURS)

Figure 12